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Abstract

Smouldering fires in wood pellet silos are not uncommon. The fires are often difficult to deal with and extinguishment is a lengthy process. Injection of inert gases to prevent oxygen from reaching the smouldering fire zone and suppress combustion is a new firefighting strategy. This article argues that injection of inert carbon dioxide (CO_2) into the silo headspace is unsafe. Carbon dioxide is generally available as a liquid under high pressure. When discharged, small particles of dry ice are formed. The rapid flow of particles can generate considerable amounts of static electricity, which can act as a source of ignition if ignitable pyrolysis gases are present. This article discusses a serious wood pellet smouldering fire and silo explosion in Norway in 2010, which took place when firefighters discharged portable CO_2 fire extinguishers into the headspace. The attempt to suppress the fire may have ignited pyrolysis gases. The article examines selected guidelines, standards, wood pellet handbooks and other literature and argues that the electrostatic hazard is widely under-appreciated. In the past, major explosions have been attributed to electrostatic ignition of flammable vapours during the release of CO_2 for fire prevention purposes. There is evidence to suggest that those early lessons learned have at least partly passed out of sight.

Keywords:
smoldering fire; silo; firefighting; explosion; carbon dioxide; static electricity

Highlights:
- *deep-seated smoldering fires in wood pellets generate pyrolysis gases*
- *flammable pyrolysis gases can travel and accumulate, e.g. in the silo headspace*
- *fires cannot be fought with water, novel approaches call for injection of inert gas*
- *injection of carbon dioxide may generate static electricity, leading to silo explosion*
- *industry standards and pellet handbooks largely silent on the hazard*

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1 Introduction

1.1 Smouldering fires in wood pellet silos

This paper in concerned with unintended ignition of pyrolysis gases produced by a smouldering fire in a wood pellet storage confinement. Although a smouldering fire may start for several reasons, two causal pathways appear to be common:

- Freshly produced wood pellets may self-heat because energy is liberated from e.g. chemical oxidation or moisture absorption. Heat loss is largely a surface-based phenomenon and because of the low surface-to-volume ratio of a large pile, any process that generates heat will slowly increase the temperature inside the pile. Pockets may form where the temperature of the contents can rise to the temperature necessary to produce spontaneous ignition. This produces an oxygen deficient smouldering fire deep inside the pile.

- Wood pellets are friable and generate dust and fines when handled in the logistics chain. This dust ignites easily, e.g. from overheated electric motors or conveyor bearings, or from mechanical friction heat between conveyer belts and accumulated pellets, fines and/or dust. Small pieces of smouldering material are difficult to detect and embers may migrate in the band conveyor systems and start smouldering fires in the storage silos.

A small smouldering fire deep inside a storage silo is difficult to detect and may develop into massive storage fires and cause considerable damage to process equipment and property [1].

1.2 Pyrolysis gases

Before developing into an open surface fire, an oxygen deficient smouldering fire generates flammable pyrolysis gases rich in e.g. toxic and flammable carbon monoxide that can travel and accumulate. Pyrolysis gases may create an ignitable atmosphere in the headspace of the silo.

An internal explosion may result when the combustion zone eventually reaches the surface layer or if a source of ignition is present in the headspace. This paper is specifically concerned with potential sources of ignition introduced by firefighters.

Although this paper discusses smouldering fires in wood pellets, a smouldering fire in any type of combustible material can generate flammable pyrolysis gases.

1.3 Water unsuitable for smouldering fires

Surface fires in wood pellets can be fought with water, which should be applied gently not to kick up dust and create conditions for a dust explosion. Applying water to a smouldering fire located deep inside a pile presents major practical challenges however. In addition, the usage of water has serious drawbacks. Most pellets are hygroscopic and expand when absorbing moisture. When fully saturated with water, compressed pellets may expand about 3.5 times. The wet pellets are sticky and expansion forces may lead to agglomeration and compaction creating a very hard and compact plug.

This creates difficulties during clean-up when the hard material must somehow be broken up for removal, at times requiring a jack hammer. Worse, the expansion may force agglomerations of pellet material to adhere to the walls of the silo, creating hangings or arch formation inside the silo. The sheer force of the expansion may even break the silo walls [1]. Hangings may also expose the silo walls to uneven loads for which they are not designed. There are examples of silos that have tipped over due to excessive application of water during firefighting [2].

1.4 Alternative firefighting strategies

The challenging nature of fighting fires in wood pellet silo and the drawbacks of using water have led research programmes to explore alternative firefighting strategies, particularly the injection of inert gases. Inert gases have the advantages of depleting the oxygen available for combustion, of quenching the pyrolysis and of lowering the risk of ignition of flammable pyrolysis gases in the headspace. The most commonly available inert gases in large quantities are nitrogen and carbon dioxide.

2 Material and methods

This article examines a case report of a serious silo explosion in Norway in 2010. The silo, which held freshly made wood pellets, experienced a deep-seated smouldering fire. The explosion took place when firefighters attempted to quench the headspace using portable CO_2 fire extinguishers. This article argues that electrostatic discharges from the release of carbon dioxide may have ignited pyrolysis gases in the headspace, resulting in the explosion.

The article examines major standards, guidelines, recent editions of frequently cited pellet handbooks and other literature, versions as per mid-2016. The article presents examples where the hazard is not stated; where the standard, guideline or recommended practice give potentially ill-advised recommendations, and where the absence of a warning may have serious consequences.

3 Theory

3.1 Carbon dioxide and static electricity

The ability of carbon dioxide to generate static electricity has been known for almost a century. Electrification effects associated with sliding contact between solid CO_2 and metal surfaces were reported as early as 1925. German experiments in the 1950s confirmed that static charging does not occur during the release of purely gaseous CO_2, that charging associated with the flow of liquid CO_2 is negligible and that strong charging occurs only when solid CO_2 particles are present. Butterworth and Dowling [3] provide a good overview of this early work.

3.2 Portable CO_2 extinguishers

A portable CO_2 extinguisher comprises a CO_2 storage cylinder, a control valve, a delivery tube and a directional horn. The storage cylinder contains liquid CO_2 under its saturated vapour pressure, which at 20°C is 5.6 MPa. When released, the carbon dioxide undergoes a change of phase from liquid to a mixture of gas and solid. To avoid the risk of electrocution when employed against fires involving electrical equipment, the directional horn is fabricated from an electrically insulating material. Most of the charge generation is believed to occur within this horn. If the extinguisher and operator are well insulated from ground, for example by an insulating floor or by footwear, the electrostatic potential can rise to 20-30 kV within a few seconds. For some extinguisher designs, potentials up to 50 kV can be attained [3].

If the operator contacts a grounded conductor, he is likely to experience an electrostatic shock. Though the shock in itself is not hazardous, it can be severe enough to deter continuing fire-fighting action and ensuing injury is a concern. The shock could lead to a loss of balance or cause the appliance to be dropped, with potentially serious consequences if the operator were in a precarious position such as atop a ladder.

3.3 Past explosions caused by the discharge of portable CO_2 extinguishers

Electrostatic discharges from the release of carbon dioxide have sufficient energy to ignite flammable fuel/air mixtures and have been responsible for

numerous serious accidents. In New York Harbour in 1966, an attempt to inert damaged tanks of the marine tanker vessel Alva Cape with a carbon dioxide extinguisher, caused naphtha vapours to explode, killing four men and injuring seven [4]. In another case, two firefighters were fatally injured in an explosion, which occurred while they used a portable CO_2 extinguisher to inert a tanker truck [5].

3.4 The Bitburg disaster

Ignition can take place even if carbon dioxide is released into steel pipework that runs underground for considerable length. A disastrous explosion took place in a JP-4 aviation fuel underground tank at a US Air Force fuel depot near Bitburg, Germany, in 1954, killing 37 people [6].

Various acceptance tests were being made on the newly constructed underground tank and its novel carbon dioxide fire extinguishing system, the first of its kind in Germany. Present were French and German officials, technicians and contractors. The roof of the underground tank was capped with iron reinforced concrete and covered with a layer of soil. Most if not all of the victims were standing on the top of the tank during a controlled activation of the thermal sensing devices that would trigger CO_2 cylinders to discharge gas into the tank's headspace.

The CO_2 cylinders were located in a half-buried concrete supply house located about 75 m from the tank and connected to the tank by a 4-inch steel pipeline which branched into two 3" pipelines that followed the circumference of the tank and terminated in four equally distanced discharge outlets . The CO_2 pipeline was buried in the ground for its entire length and the discharge outlets were installed flush with the interior tank wall surface and welded to the main steel tank. Although presumably effectively grounded, this piping arrangement conveyed electrostatically charged carbon dioxide.

One minute after the CO_2 discharge commenced, a massive explosion disintegrated the tank. The blast blew victims through the air with such force that their bodies were found between the tank and the supply house. The official investigation [6] did not identify carbon dioxide as the source of ignition; its ability to generate static electricity was only realized later [7].

3.5 Summary

Back in 1977, Leonard and Clark [5] succinctly summarized the knowledge available at the time, concluding that CO_2 fire extinguishers are perfectly satisfactory when used for their intended purpose, i.e., extinguishing a fire, but they should never be used to inert atmospheres containing flammable fuel/air mixtures.

4 The 2010 silo explosion at Hallingdal

4.1 The facility's fire history

Hallingdal trepellets is a wood pellet manufacturer located in Ål Municipality, Norway, about 200 km NW of Oslo. Raw materials are pinewood and spruce, about 50/50. The facility started production early in 2007.

On April 23, 2007, there was a serious fire, which started in a covered pit with approximately 200 m³ of dry (humidity 8%) wood chips in bulk. The chips were still warm from the drying process. An adjacent pit held wet wood chips, humidity about 50%. A wooden wall separated the two pits. The incident started as a minor smouldering fire. Firefighters attempted to localize and contain the fire using various means such as infrared imagery, CO_2 extinguishers, fire hoses and steam lances, but the efforts were largely ineffective. Suddenly, the fire intensified and over a time span of less than 10 min. developed into a blaze that spread rapidly to the production building. The fire rendered the facility a complete loss.

The facility was rebuilt. To avoid repeat fire escalation, the dried wood chips were kept in a silo and the quantity stored was reduced. In addition, a new concrete wall separated the wood chips area from the production building. The following year, on July 5, 2008, there was a new fire in the wood chips area. This time the damage was limited thanks to the fire safety improvements.

On July 5, 2010, the facility saw a third fire, this time in a 7,742 m³ silo for final product that had been completed the year before. Eventually, the silo exploded while firefighters attempted to quench the fire with inert carbon dioxide.

4.2 The silo

The silo was made of steel with a diameter of 24 m, a wall height of 15 m and a cone roof resulting in a total height of 21 m. A band conveyor system terminating below the apex dumped freshly produced pellets into a pile below. To draw pellets, sliding doors in the floor could open and dump pellets onto a conveyor band. These doors were closed at the time of the fire. Temperature sensors hung on wires running from the roof to the floor were monitoring the temperature inside the pellet pile.

To enhance natural ventilation of the headspace, there was a 3 cm air gap between the silo shell and roof. The total area of the airgap was about 2 m². The roof was made of thin metal sheets joined to the supporting frame with metal bolts and plastic nuts. The total weight of the roof construction was about 27 t. Because plastic nuts were used, the roof construction was believed to be weak and able to serve as overpressure relief in case of an internal explosion [8].

4.3 Smouldering fire

Shortly after midnight on July 5, 2010, at 0043 hours, the fire and rescue services were called to the facility. Sensors in the pellet pile showed rising temperatures. The silo was slightly less than 50 percent full, containing an estimated 3,500 m³ of wood pellets. The on-scene-commander arrived at 0130 hours. He soon decided to request a shipment of nitrogen from Yara, a large producer of industrial gases located in Porsgrunn some 320 km away. At 0141 hours, the pile temperature had increased to 60°C and an alarm came in from the silo's fixed CO detector. At 0242 hours, infrared imagery was able to detect an increased temperature of the silo's outer shell, the pile temperature stayed at about 60 °C. Smoke was now visible above the roof area. Fire fighters received notice that a Yara nitrogen tanker truck was expected to arrive at noon.

CO_2 bottles from nearby power stations were mobilized and arrived at 0635 hours. Only 22 bottles were available, about 220 m³ of CO_2 gas, just 5 percent of the headspace volume. A revised time estimate pushed the arrival of the Yara nitrogen tanker truck to mid-afternoon, at the earliest.

Although the effect of CO_2 injection was expected to be limited because of the modest quantities available, a CO_2 attack was decided, in the hope that it at least might attenuate the fire until nitrogen supplies arrived. CO_2 would be injected manually from a fixed platform located next to a roof inspection hatch. A crane hoisted a basket with the bottles onto the platform and two firefighters with breathing apparatus climbed the silo's exterior ladder to manually discharge the CO_2 through the inspection hatch.

4.4 Explosion

At 0845 hours, when discharging the fifth CO_2 cylinder, the silo exploded. The force of the explosion lifted the 27 t roof upwards and flames of burning gases shot out of the hatch opening and horizontally from the circumferential edge of the roof. Although the entire roof is believed to have lifted about 0.5 - 1 m, it re-seated without collapsing. There was no structural damage to the platform and the firefighters were able to descend the exterior ladder to ground level.

The firefighters suffered burn injuries to the ear, back and hand. Luckily, their full personal protective equipment offered excellent burn protection. There was evident heat blister damage to a helmet and to a facial mask. The hood and jacket saw minor burn-through damage. One firefighter suffered burns to his

hand because he had taken off one of his bulky gloves in order to operate the valve on the CO_2 cylinder.

After the explosion, the silo was considered a complete loss and an excavator was called in to tear a hole in the silo wall in order to empty the silo and extinguish the burning material outside. When the silo was torn open, a large surface fire was visible inside the silo.

4.5 Investigation

Based on readings from the temperature sensors hung on wires inside the silo, the smouldering fire was believed to have started near the centre of the pellet pile. Pellets had not been drawn from the silo for two weeks and it was speculated that self-heating of pellets deep inside the undisturbed pile could have started an oxygen deficient smouldering fire. Pyrolysis gases would then accumulate in the silo's headspace.

The investigation identified the likely source of ignition to be a sudden combustion zone break-through to the surface layer of the pellet pile. The wind was blowing steady at 8-10 m/s and the investigation report argued that sufficient turbulent entry of air through the 3 cm airgap between the shell and roof could have formed an ignitable pyrolysis gas mixture under the roof. Furthermore, that additional air had entered the headspace through the open hatch during the injection of CO_2 due to backdraft and wind.

The investigation did not identify electrostatic effects due to injection of carbon dioxide as a possible source of ignition. The national independent highly qualified senior fire investigator later stated (personal communication) that this mechanism was unknown to him.

4.6 Source of ignition

Ignition of pyrolysis gases may either have been caused by a sudden combustion zone break-through to the surface layer or by static electricity. There is no empirical basis for this article to enter a discussion on the likelihood of either mechanism. From an industrial accident prevention perspective, what matters most is the lack of awareness of the hazard of electrostatic effects amongst emergency responders and accident investigators.

5 Discussion

5.1 Flammability, ignitability, inerting and purging

Although it is common practice to refer to a combustible gas such as methane as a "flammable gas", a homogeneous mixture of gas (the fuel) and air will only propagate a flame if the concentration of the fuel is within well-defined limits. In concentrations below the lower flammable (or "explosive") limit, the fuel/air mixture is too dilute; it is said to be too lean. Above the upper flammable (or "explosive") limit, the fuel/air mixture is said to be too rich. The mixture is only ignitable within these two limits. Limits are determined experimentally and often expressed as percent volume fraction at 25 °C and standard pressure.

Flame cannot exist below a limiting flame temperature. This can explain two phenomena. First, the effect of increasing the concentration of a non-combustible (inert) gas can be understood by viewing the inert gas as thermal ballast that quenches the flame temperature to a level below which the flame cannot exist. Carbon dioxide is therefore a more effective inert gas than nitrogen due to its higher molar heat capacity. Second, as temperature increases, the ignitable range widens because less combustion energy need be released to achieve the limiting flame temperature [9].

For methane, the ignitable range is 5 – 15 % volume fraction. Heavier hydrocarbon gases have lower limits, the ignitable range for butane is 1.8 – 8.4 % volume fraction. Carbon monoxide, a common pyrolysis gas, has an unusually wide ignitable range of 12.5 – 74 % volume fraction. Hot mixtures of pyrolysis gases and air are therefore often in the ignitable range and able to cause an explosion, if they meet an ignition source.

It is important for the discussion that follows to clarify precisely what is meant by inerting and purging. Where an ignitable mixture is contained, such as in a processing vessel, the atmosphere can be made oxygen deficient by introducing enough non-combustible (inert) gas to make the mixture non-ignitable. This technique is known as inerting in NFPA 69 [10] and NFPA 77 [11]. The key characteristic is that the mixture of flammable gas and air is in the ignitable range *before* an inert gas is introduced.

The concern is different during start-up of process equipment. Before a flammable gas is introduced into a system containing air, it is often recommended that the air in the system be diluted by an inert gas such as

nitrogen, carbon dioxide, or argon to low concentrations so that when flammable gas is introduced, an ignitable mixture cannot form within the system. In the terminology commonly used in the petrochemical industry and in NFPA 56 [12], this practice is known as "purging into service".

A somewhat similar situation arises during shut-down. If a system that contains a flammable gas is to be taken out of service, the gas can be diluted by an inert gas to low concentration, so that when air is introduced, an ignitable mixture is not created within the system. This practice is known as "purging out of service" [12].

While the two purging practices are similar in principle, it is useful to have two distinct concepts because purging out of service requires much larger quantities of inert gas than purging into service. Carbon dioxide may be a suitable inert purge gas because both purging practices ensure that an ignitable mixture never forms in the system. Hence, in theory, the introduction of a possible source of ignition due to static discharges is of no concern.

Unfortunately, because an inert gas is used, both purging practices may loosely be referred to simply as "inerting". But purging should not be confused with inerting where an ignitable mixture of flammable gas and air is made safe by adding an inert gas. Carbon dioxide is unsuitable for this purpose.

5.2 German standards

Much of the early knowledge and insights regarding the ability of CO_2 to create hazardous electrostatic discharges is based on work carried out in Germany, in particular insights gained after the disastrous Bitburg explosion in that country. It is therefore noteworthy, that the hazard has no prominent place in German rules and guidelines.

In Germany, the dangerous substances regulations are known as the Technische Regeln für Gefahrstoffe, TRGS (Technical rules for dangerous substances). The explosive atmospheres regulations are known as "Technische Regeln für Betriebssicherheit", TRBS (Technical Rules for Operating Safety). Some of the regulations overlap. The relevant regulations are TRBS 2152, which come in four parts [13–16]. Both the general section (part 1) [13] and the detailed technical requirements for preventing or mitigating a hazardous explosive atmosphere (part 2) [14] do not mention the electrostatic discharge hazard.

It is true, that part two deals only with purging into and purging out of service, in German terminology referred to as "partial inerting" and "total inerting" respectively, for which static discharges, in principle, are of no concern. Still, a warning about electrostatic discharges might be relevant, for instance in section 2.3.4, which deals with vessels in vacuum service, for which the safety system can be so designed that detection of an operational upset with air ingress will trigger an automated inerting response. The absence of a warning is noteworthy because the standard lists other types of situations where carbon

dioxide (and nitrogen) are unsuitable inerting agents, e.g., that fine dusts of certain light metals may undergo chemical reaction with these gases.

Part three [15] of TRBS 2152 does make passing reference on page 29 to another standard, TRBS 2153 [17], which deals with static electricity, but there is no specific mention that the inert gas carbon dioxide itself could be a source of static electricity. The TRBS 2153 standard on electrostatics clearly identifies the static hazard on pages 64-65 out of 128. It states that processes that may produce considerable static discharge include: "pneumatic transport of solids, a release of pressurized gas with solids, *the discharge of liquid carbon dioxide*, industrial vacuum cleaners and spray painting operations" [17] (emphasis added).

The TRBS 2153 standard also rather extensively covers the situation when an ignitable mixture of flammable gas and air is to be made safe by adding an inert gas, which is referred to simply as "inerting", similar to the terminology of NFPA 69 and NFPA 77. The standard cautions that the discharge of a fire extinguishment agent, which could produce static discharges, should never be carried out for test purposes, when a potentially explosive atmosphere exists. The standard specifically states that CO_2 and wet steam (steam with droplets of water) are unsuitable inerting agents for this purpose [17]. This is the closest reference to the lessons learned from the Bitburg disaster.

In conclusion, it is probably fair to assume that safety-conscious readers with a prior concern or expectation that CO_2 is able to create hazardous electrostatic discharges will consult the TRBS 2153 standard on static electricity [17] and see their expectation confirmed. Safety-conscious but unsuspecting readers, however, are likely to consult the TBRS 2152 standard on flammable atmospheres only. A careful examination of the four documents that comprise this standard will provide no clue as to the electrostatic hazard.

It is true that information on the electrostatic hazard *does exist*. A German fire safety professional kindly informed that the European Industrial Gases Association (EIGA) covered the issue in a safety newsletter [18], which is also available in English [19]. Some German fire safety professionals recommend that an evaporator is used, if CO_2 agent is used (personal communication). This article argues however, that there is considerable evidence to suggest that the hazard is not widely appreciated. For instance an article in a German firefighter magazine [20] discusses two cases of fighting smouldering silo fires using CO_2, evidently unaware of the electrostatic hazard.

5.3 NFPA standards

NFPA standards share the same weaknesses as the German ones, confirming the electrostatic hazard of carbon dioxide to those readers who consult a standard on static electricity because they already suspect the gas to have these properties, but are otherwise mostly silent on the issue. NFPA 77 [11] on static electricity clearly states that carbon dioxide from high-pressure cylinders or fire

extinguishers should *never* be used to *inert* a container or vessel (emphasis added).

NFPA 69 [10] on explosion prevention systems does neither mention electrostatic effects nor refer to NFPA 77 although the standard lists the following purge gas sources as acceptable: commercially available inert gas, such as nitrogen, carbon dioxide, argon, or helium, supplied from high-pressure tanks or cylinders. Lamentably, the standard's usage of the terms purging and inerting is not entirely unambiguous.

NFPA 12 [21] on carbon dioxide extinguishing systems provides ambiguous advice on the electrostatic hazard. Annex A states that the discharge of liquid carbon dioxide is known to produce electrostatic charges that, under certain conditions, could create a spark and duly refers to NFPA 77. The standard also specifies, that "carbon dioxide fire-extinguishing systems protecting areas where explosive atmospheres could exist *shall* utilize metal nozzles, and the entire system *shall* be grounded" [21, Sec. 4.2.1] (emphasis added). The first issue of concern is if the reader realizes that an ignitable (and explosive) atmosphere can exist not only when flammable liquids give off vapours but also when pyrolysis gases have accumulated. The second issue of concern is if effective grounding is sufficient to prevent hazardous electrostatic discharges – the Bitburg accident would appear to contraindicate this. The third and perhaps most important issue of concern is the standard's ill-conceived advice on the application of CO_2 to "deep-seated fires involving solids subject to smoldering" [21, Sec 5.2.3]. This is precisely the situation where pyrolysis gases may have accumulated in the headspace to an extent where they are in the ignitable range – but the reader may not have realized this, and the standard does not identify the potential presence of flammable pyrolysis gases . The nub of the issue may well be lack of clarity in the meaning of the terms "fire" and "extinguishment", which are not defined in the standard's terminology section. The application of CO_2 is excellent for extinguishing a fire with flames, but unsuitable for quenching a deep-seated smouldering fire without flame.

Annex A of the NFPA 850 [22] covers spontaneous heating, hotspot formation and fire in coal silos Firefighting in coal silos is a long and difficult activity , the standard says, but carbon dioxide and nitrogen have been used successfully as gaseous inerting systems. The standard specifically states that carbon dioxide vapour has proven to be effective in quickly establishing an inert atmosphere in the space above the coal, which prevents the creation of an explosive atmosphere there. Carbon dioxide has the advantage over nitrogen of being denser than air, the standard says. Because nitrogen has a density similar to air it must be applied at numerous injection points around the silo to ensure that it displaces available oxygen. Compared to carbon dioxide, the standard says, nitrogen requires more injection equipment and a larger quantity of agent.

It is true that injection of carbon dioxide can prevent the creation of an explosive atmosphere in the silo headspace. This article argues however, that the procedure is unsafe because plant personnel or firefighters usually have limited means to determine if pyrolysis gases present in the headspace are

already in the ignitable range when the injection begins. The NFPA 850 standard is silent on the electrostatic hazards of carbon dioxide.

5.4 Special report on US agricultural silos

Fires and explosions in agricultural silos have been responsible for the deaths and injuries of firefighters and civilians and have led to large loss of property. In response to a number of agricultural silo emergencies, the United States Fire Administration issued a Special Report in 1998 [23] in order to communicate significant lessons learned.

Spontaneous ignition and smouldering fires in agricultural silos present challenges to firefighters. The report states that extinguishment may be accomplished by injecting nitrogen or carbon dioxide into the silo using special fittings and piping. The report is silent on the electrostatic hazards of carbon dioxide.

5.5 Swedish contributions

Sweden is the only country in Scandinavia with a significant domestic pellet production. The domestic pellet market is mature and pellet consumers are diverse, from single-family households, industry, district-heating systems and large Combined Heat and Power (CHP) plants. For many years, Sweden was the largest consumer of wood pellets in the EU and was only in 2012 surpassed by Italy and Denmark [24].

Ambitious and foresighted research programmes have been undertaken by the Swedish National Testing and Research Institute (in Swedish: Sveriges Prövnings- och Forskningsinstitut, abbreviated to SP) to address, amongst others, the challenges with wood pellet silo fires. In 2006, the SP reported the results of an experimental study on fire extinguishment in wood pellet silos [25]. The study concluded that extinguishment should be carried out with injection of nitrogen or carbon dioxide, primarily into the bottom of the silo, although injection into the headspace at an early stage could be considered in order to eliminate explosion risks, i.e. inerting. According to the report, the use of carbon dioxide merely presents practical problems because injection lances freeze up – the report is silent on the risk of electrostatic discharges.

The inert gas technique was applied e.g. in 2007, when a pellet silo in Kristinehamn, Sweden, experienced a smouldering fire due to self-ignition [26]. Tanker trucks with nitrogen and carbon dioxide were called to the site. Preparations for injection of nitrogen into the bottom of the silo were repeatedly delayed due to multiple complications when drilling openings in the concreate silo and with the improvised making of custom injection lances. Not to waste time, carbon dioxide was therefore introduced into the silo headspace through a fire hose. The hose froze up and plugged repeatedly. A total of 35 t of carbon dioxide were injected without incident. Evidently, the emergency responders and technical advisors from SP were unaware of the risk of electrostatic discharges.

In 2011, the novel inert gas approach was communicated widely in Biomass Magazine [27] and Canadian Biomass [28], without mention of the electrostatic hazard. The Swedish experiences have also found way into pellet handbooks, e.g. [1] published in 2012, which merely states that attempts to use carbon dioxide without a vaporisation unit have caused many unsuccessful extinguishing operations as the supply hoses/lances /nozzles and the bulk material close to the injection point tend to freeze quickly, blocking further gas injection. An almost verbatim description is provided in an otherwise comprehensive publication on health and safety aspects of solid biomass published in 2013 by the International Energy Agency [29]. The publications are also silent on the risk of electrostatic discharges.

In 2013, the Swedish Civil Contingencies Agency issued a report on silo fires, written in English and clearly intended for an international audience [2]. This report, at last, does advice against the use of CO_2 due to risks of static electricity during gas injection. But the report is a sole voice of caution in an abundance of standards, guidelines and literature that seem unaware of the hazard.

5.6 De-learning

Policy makers and risk analysis professionals may wish that the state of knowledge is always increasing, that accident prevention knowledge is continuously improving, as if obeying a fundamental law of nature. This case shows that the opposite can occur. That important information on hazards, learned the hard way through investigation of past disastrous explosions, can pass out of sight. This appears to have happened in the fast growing wood pellet sector where difficulties with smouldering fires has led to new techniques for firefighting which employ inert gases, of which carbon dioxide is one.

With the increase in the quantities of solid biomass handled, this knowledge loss becomes significant. The smouldering fires are difficult to deal with, water is not a suitable extinguishment agent, and firefighters, who are men of action, can become frustrated if having to wait idly for supplies of nitrogen to arrive. If carbon dioxide extinguishers are available it may be tempting to "do something" to retard fire development. This can result in explosions with loss of life.

5.7 Media-shifting

The past decade has seen a major increase in the consumption of wood pellets. The growth has been mirrored in an increase of pellet related accidents involving fires, dust explosions and toxic gases, some of which have been poorly investigated, causes not identified and lessons not learned [30,31]. A small but growing body of literature argues that bioenergy and other low-carbon energy systems present major accident hazards [32–35]. There are even indications that the number of accidents in the bioenergy sector is growing faster than the energy production [34].

Utmost care should be taken to avoid so-called media- shifting [36], i.e. that the resolution of a problem within one domain, the environmental, creates a new problem in another, the workplace safety domain.

6 Conclusion

Water is unsuitable for fighting fires in wood pellet silos. Recent alternative firefighting strategies call for injection of inert gases. The use of carbon dioxide is unsafe. Ignitable pyrolysis gases can be present in the headspace and electrostatic discharges from the release of carbon dioxide from high-pressure cylinders have sufficient energy to ignite the gases leading to silo explosion. The evidence presented in this paper supports a general conclusion that that the electrostatic hazard appears widely under-appreciated, across countries.

Although the electrostatic hazard has been known for more than 50 years, many standards, guidelines, recent editions of frequently cited pellet handbooks and other literature cover the hazard superficially or do not mention it at all. The ability of oxygen-deficient (smouldering) fires in solid combustibles to produce ignitable pyrolysis gases that can travel and accumulate in e.g. the headspace of a storage confinement is also insufficiently covered. The situation appears particularly grave for NFPA 12 on carbon dioxide extinguishing systems, which gives ill-conceived advice on the application of CO_2 to deep-seated fires involving solids subject to smouldering. NFPA 69 and NFPA 850 should also be revised to highlight the hazard.

It is true that standards on static electricity, e.g. NFPA 77, do mention the electrostatic hazard of carbon dioxide. Safety conscious readers are likely to consult such standards only if they already suspect carbon dioxide to have electrostatic properties; unsuspecting readers will unlikely be alerted to the hazard.

The standards should be revised for improved terminology, in particular the difference between inerting and purging, and the difference between extinguishing a fire with flames and quenching a deep-seated smouldering fire without flame. Where relevant, the standards should also stress that an ignitable atmosphere may exist, not only when flammable liquids give off vapours, but also if pyrolysis gases are present.

The key contribution of this paper is to draw attention to the hazards of releasing liquid CO_2 into environments where an ignitable atmosphere may exist. Important fields of application, such the practice of installing carbon dioxide extinguishment systems in the cargo hold of marine vessels, some carrying wood pellets susceptible to smouldering fires, could not be covered in this work. Conditions in the cargo hold are comparable to those in a silo and

the explosion hazard is likely the same. More research into the subject is needed.

7 Conflicts of interest

The author has no conflicts of interest to declare.

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